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AN ATTEMPT TO FRAME A WORKING HYPOTHESIS OF THE CAUSE OF GLACIAL PERIODS ON AN ATMOSPHERIC BASIS.

(Continued)

III.

LOCALIZATION OF GLACIATION.

THE problem of localization is in some sense independent of the fundamental hypothesis offered in this paper, and the suggestions which follow may be accepted or rejected without carrying necessarily an approval or disapproval of the main hypothesis.

The remarkable distribution of the great ice-sheets.—The chief centers of the Pleistocene ice-sheet lay on the north-northeastern plains of North America, and on the northwestern quarter of Europe. On the northwestern Cordilleras there was also a notable center, though it does not appear to have equaled the others in rank.[1] The north-northeastern American centers are properly regarded as chief because the spread of the ice-sheets from them was much more extensive than from the other centers, and because they were not aided essentially by mountainous points of origin, for neither the Labradorean nor the Keewatin centers appear to have been initiated by mountainous elevations. It was a development of glaciation on plains, or at most on plateaus. This fact renders the American ice-fields conspicuously chief among all that developed in Pleistocene times. The glaciation of Europe was centered upon mountains; and remnants of glaciation still linger on the mountain heights of most of the old glacial fields, giving ground for the belief that the local topographic features were there important factors. The glaciation of northwestern Europe would possibly have been rather scant if it had received no greater topographic aid than was afforded in the Keewatin field, but apparently it would not have been absent.

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[1] This statement is perhaps open to some question. It is quite certain from field observations that the glaciation of the Cordilleran plateau in the United States and in British Columbia as far north at least as 51° Lat. was much feebler than that of the Mississippi basin at corresponding latitudes and much lower present altitudes. It seems also clear that the ice of the north Cordilleras did not creep out upon the plains to an extent at all comparable to the spread of the Scandinavian ice-sheet upon the plains of Europe. Considered from these points of view, and they seem to be the important ones, the statement can scarcely be questioned seriously. The evidences of glaciation on the mountainous border facing the Pacific from 48° northward are, however, quite impressive. They find their climax perhaps in the 4000 or 5000 feet of glacial débris which Russell reports in the foothills of the St. Elias range. In view of this it may perhaps be insisted that the glaciation of this region was exceptionally concentrated on the Pacific border, because of the abrupt rise of the surface and the height of the mountains, and that the glacial discharge toward the Pacific was also exceptionally effective because the high gradient; so that, taking this intensification into account, the sum total of ice formation and ice action in this region may not have been so much inferior to that of the European area as the surface distribution might seem to imply.

It has often been remarked that the Pleistocene glaciation was gathered about the north Atlantic, but it can scarcely be too much emphasized that the greatest of the glacial areas, and by far the most phenomenal, because of its plain topography, lies on the *western*, or what we are accustomed to regard as the *windward*, side of the Atlantic.

It is further to be noted, that on the western side of America, the glaciation, though notable, was still seemingly much inferior to that of the great northeastern plains; and this in spite of its mountainous character and its adjacency to the great Pacific Ocean, a topographic and hydrographic conjunction which expresses itself now in the most vigorous glaciation outside of the polar circles.

More or less nearly contemporaneous with the growth of the foregoing great ice-sheets, local glaciation developed on nearly all the mountain heights of the earth, whether in the northern or the southern hemisphere, and whether in high or low latitudes. This seems to imply an intensification of glacial conditions generally, but at the same time to indicate that the great ice-sheets were dependent on some special agency of localization. In saying that these scattered areas of glaciation were approximately contemporaneous, no dogmatic assertion is intended relative to the exact contemporaneity of glaciation or to its alternation in the northern and southern hemispheres, nor respecting the doctrine of migration of glaciation in longitude. Observational data are yet insufficient to decide these questions. It is obvious, however, that the hypothesis under consideration postulates essential contemporaneity throughout the globe.

The constructive pole of the winds.—As a possible factor in the localization of glaciation, I venture to offer the suggestion that the axis of the earth's rotation and the axis of the atmosphere's circulation, constructively interpreted, are not identical. By the constructive axis of the winds I mean that ideal line about which the general currents of the atmosphere would be found to revolve if all minor movements were eliminated or equated and the aggregate east-west components only were regarded. In other words, it is suggested that the planetary system of circulation is obliquely adjusted to the planet. This was first suggested to me by a study of the peculiar courses of the arctic ice-drift. The polar ice-bearing currents are regarded by experienced arctic navigators as concrete expressions of the average movements of the atmosphere. To be sure, the ice-drift is affected by the ocean currents, but these are also, in the main, the results of the average direction and force of the winds, though they do not so immediately and definitely express it as the ice-drift, because they are also influenced by more remote agencies.

If the axis of the currently postulated "circumpolar whirl" of the atmosphere coincided with the axis of the earth, and if it were the poleward incurving spiral of the winds that swept the surface of the polar sea, the average ice-drift should assume, or tend to assume, a corresponding incurving spiral. The ice should crowd in toward the pole and rotate upon itself in a direction opposite to the hands of a watch. If this were true, the current which carried Nansen from east to west should have flowed from west to east.

If the axis of the "circumpolar whirl" coincided with the axis of the earth, and it were the *outward-running* spiral that swept the surface of the sea, the ice-fields should rotate in the opposite direction with a centrifugal tendency which should carry the ice outwards and press it against the adjacent continents and give a voluminous discharge down the north Atlantic. An attempt to drift *toward* the pole in such a system would be an absurdity, and Nansen's feat would be inexplicable.

Observed ice-drift.—Neither of these are the phenomena observed. On the contrary, as now abundantly demonstrated, particularly by the remarkable drifts of the Jeannette and the Fram, the average movement near the coast of northern Asia and Europe is westward and slightly northward. This course is held until Greenland imposes itself as a barrier. The outer margin of the ice flow is then forced southward, but immediately it reaches Cape Farewell it curves closely about the point (at least during the summer months) and flows northward and westward to the vicinity of the arctic circle. It here encounters a new barrier in the islands of the American Arctic Archipelago and again moves southward.

On the north coast of Greenland, so far as known, the ice presses hard upon the land, as though its normal course were southward. It flows persistently into the channel between Greenland and Grinnell Land, and gives rise to that strenuous ice-pack which has again and again been assailed by arctic navigators with such great daring and such little success. The recent adverse experiences of the Windward and the Fram are but a renewed expression of the persistence of this south-southwestward drift of the ice currents.

On the north side of the Arctic Archipelago, west of Greenland, the ice crowds hard against the shore, and has thus far prevented the full penetration of Jones Sound or any of the other straits between the northern range of islands. The blocking of Jones Sound appears to be the result of an eastward as well as southerly crowding of the ice.

Farther to the west Banks Strait and McClintock Channel together form a continuous and rather broad water way, beginning in longitude 130° west and stretching southeasterly to longitude 95° west. This channel is always tightly jammed with ice pressed in from the northwest. So persistent and strenuous is the pressure of this ice-pack that it constitutes an effectual barrier to the northwest passage, and has thus far mocked all attempt to force it. This implies a definite and persistent movement from the northwest to the southeast.

It appears, then, that from far east of Greenland to the western limits of the northern archipelago there is a definite convergence of the ice currents toward a point located somewhere north of Hudson Bay, *i. e.*, a point lying to the north of the two great centers of Pleistocene glaciation, the Labradorean and the Keewatin, and on a meridian that runs between them.

It is interesting to note that the point of convergence lies in the general vicinity of the magnetic pole. and this obviously leads to the further suggestion that there may be some genetic connection between the two as yet undetermined.

Concurrent in import with this is the fact that on the opposite side of the north pole the coasts of northern Asia and Europe become partially free of ice each season. This, although doubtless partly due to the effects of the fresh water borne in by the great rivers of those coasts, is probably none the less an expression of the fact that the polar ice is not crowded down upon those coasts; for if it were, its great mass would completely overwhelm the effects of even the great Siberian rivers. This phenomenon, taken in connection with the direct observations of the ice-drift made by De Long, Nansen, and others, leaves little room for doubt that the great polar ice-field drifts away from the Eurasian coast and crowds toward Hudson Bay. The meridian of 90° may be taken as rudely representing the axis of this converging ice-drift. It is interesting to note that this same meridian bisects the Mississippi valley and crosses the southern apex of the great American glacial field.

Distribution of arid zone.—Correlated with this remarkable phenomenon is an equally remarkable distribution of the great desert tracts of the eastern hemisphere. Commencing on the Atlantic coast of Africa between 10° and 30° north latitude, the arid belt stretches north of east across Africa and Asia until in Mongolia it lies between 30° and 50° north latitude. That is to say, in this stretch of 70° or 80° in longitude it has advanced 20° in latitude. If now we select the meridian at 90° east, at or about which the desert area reaches its northern culmination, and follow this through the pole to a point 20° beyond on the meridian of 90° west, we are in the vicinity of the point towards which the arctic ice-drift seems to concentrate. And if we follow the same meridian southward we reach the point in the Mississippi valley where the ice-sheet had its southernmost extension. It is to be noted further that this last point coincides with the region where a large percentage of the cyclones which descend from the northwest curve about and take northeasterly courses.

If there were space here to enter into other particulars, additional coincidences of an apparently significant nature might be found. The inference drawn is that the axis of the main polar whirl, if indeed the polar movement can be called a whirl, is not coincident with the axis of the earth, but lies at some point southward from it in the vicinity of the meridian of 90° west longitude and 20° more or less distant from the pole.

Indications of meteorological data.—As just implied, the idea entertained is not that there is a simple polar whirl whose axis is located here, but that the rather complex movements of the polar atmosphere, when combined and correlated, give a theoretical or constructive pole in this region. What is meant by this will appear more specifically from a study of the available meteorological data. Unfortunately these are yet quite imperfect and partially uncorrelated, and hence I have given precedence to the natural correlation expressed in the ice-drift. The International Circumpolar Commission has not yet combined and discussed its data. It may therefore be most convenient to have recourse to Buchan's[1] or Hann's[2] meterological maps for the general features of atmospheric pressure and circulation. An inspection of Buchan's isobaric maps shows that there are, north of 45° north latitude, two nearly permanent areas of *low* barometer and one of *high* barometer. (See accompanying sketch maps 1 and 2, based mainly on Buchan's.) The area of high barometer is located in Asia on the meridian of 100° east longitude. It may perhaps be regarded as one of the normal high areas that theoretically belong to the parallel of 30° north latitude, but which has been displaced 20° to the northward by the topographic conditions of the great Eurasian continent. Its two chief companions under this view lie, the one in the east Atlantic centering near the Azores, about 30° north latitude and 25° west longitude, the other in the east Pacific, off the coast of California, in about 35° north latitude and 140° west longitude. But the Asiatic area of high pressure seems to combine in itself also the function of a polar center, for no other center, high or low, lies between it and the pole. Moreover, it is above mid-latitude, and is nearer the parallels of the two permanent areas of low pressure of the arctic region than to those of its 30° correlatives, for it lies itself in 50° north latitude, while the arctic "lows" lie in 55° and 60° north latitude respectively.

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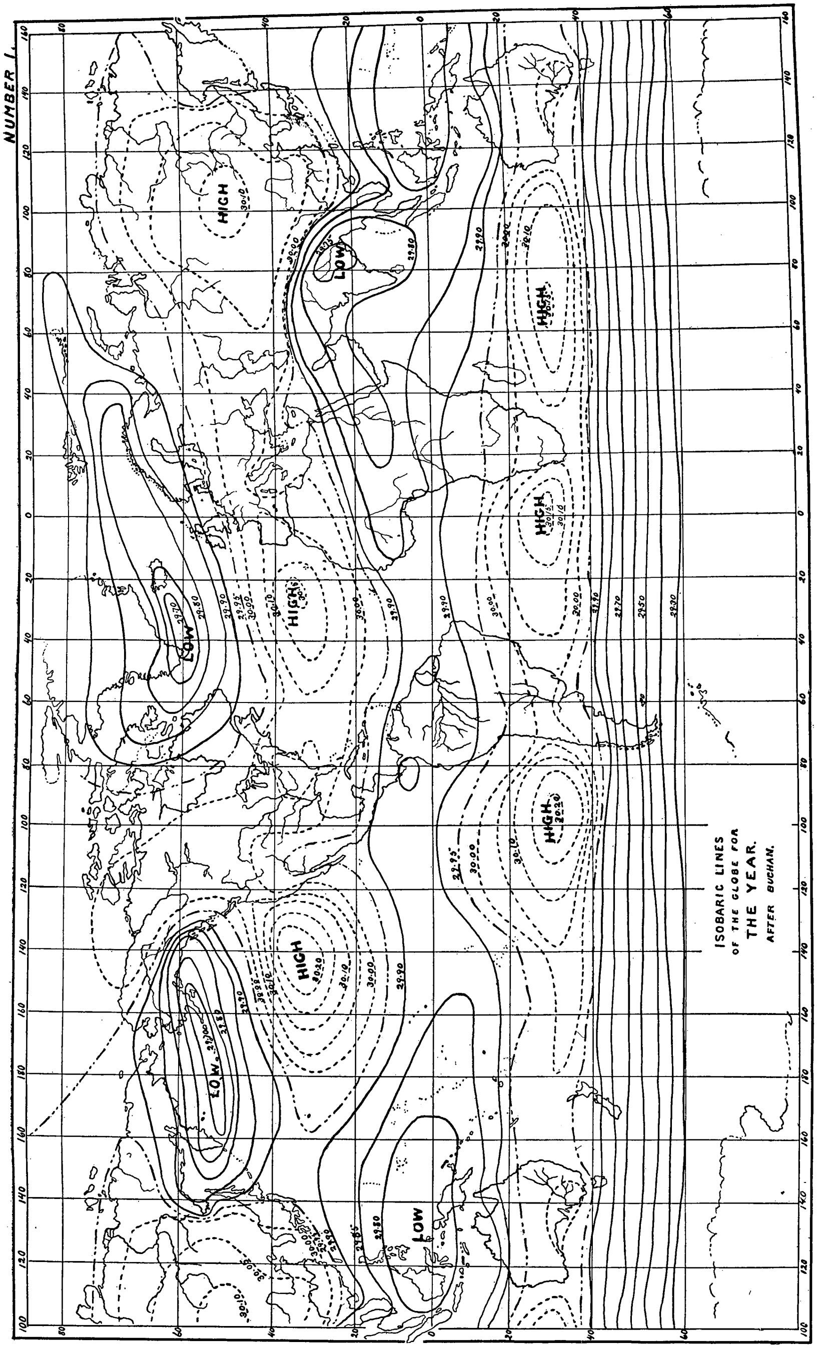
[1] Challenger Reports. Physics and Chemistry, Vol. II, Atmospheric Circulation. Maps 51 and 52. These include the main data gathered by the International Circumpolar Stations.

[2] Berghaus Physical Atlas.

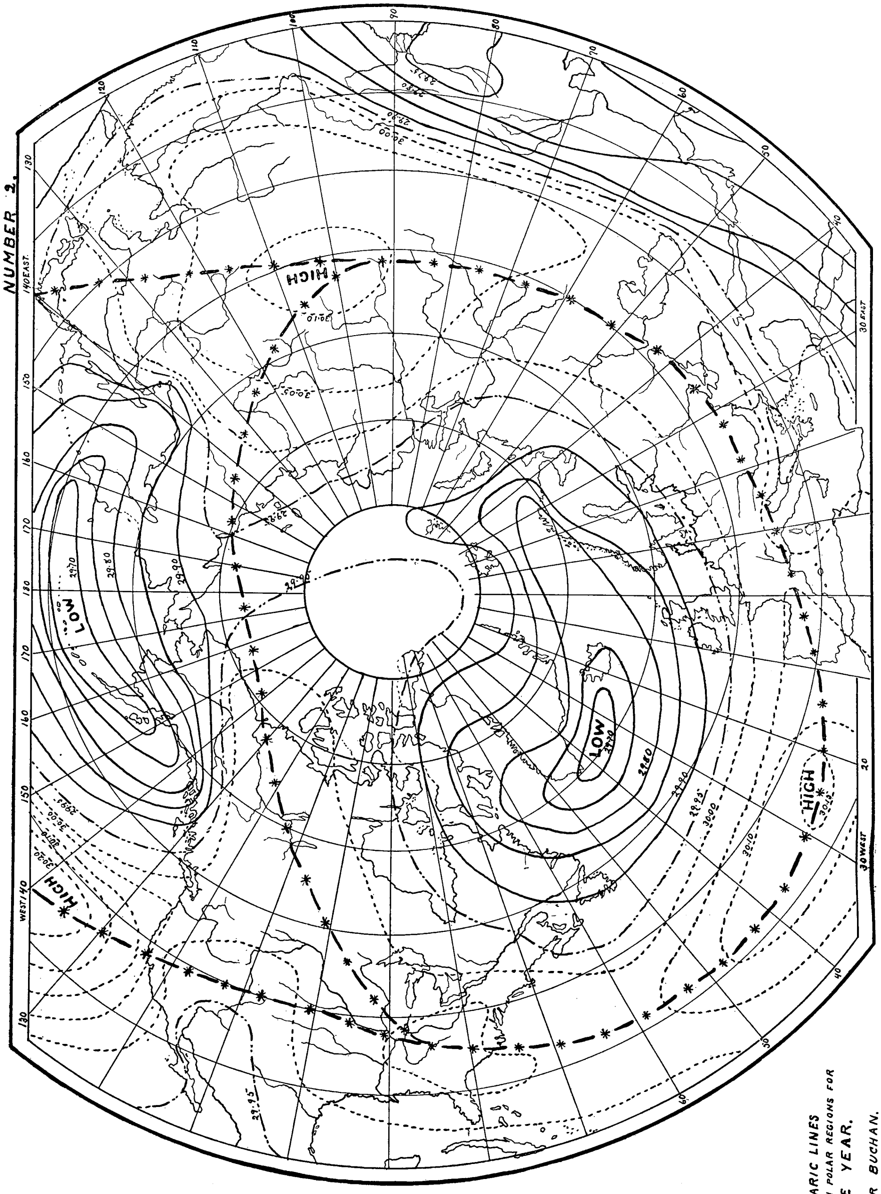
Furthermore, as shown on Buchan's map 52, these high-latitude centers are arranged about the pole at nearly equal distances from each other, the Asiatic "high" being in about 100° east longitude, the north Atlantic "low" in about 35° west longitude, and the north Pacific "low" in about 170° west longitude, *i. e.*, their successive distances from each other are 135°, 145°, and 140°. While these centers shift somewhat during the seasons, they are essentially fixed, the above statements being based on the isobaric averages for the year. These centers are therefore to be distinguished from the familiar moving cyclonic centers and are to be regarded as enduring factors which express the essentially permanent circulatory features of the circumpolar atmosphere. The Asiatic "high" is a permanent anti-cylonic area characterized by descending outward-flowing currents, attended by low precipitation and clear air. The north Atlantic

NUMBER I.



ISOBARIC LINES OF THE GLOBE FOR THE YEAR. AFTER BUCHAN.

NUMBER 2.



ISOBARIC LINES
OF THE NORTH POLAR REGIONS FOR
THE YEAR.
AFTER BUCHAN.

and north Pacific "lows" are permanent cyclonic areas with inflowing ascending currents attended by high precipitation and prevalent fogs.

Of the two "lows" that of the north Atlantic is the broader and more northerly, and appears to be the more influential factor now, as presumably it was in Pleistocene times. The north Atlantic "low," according to both Buchan and Hann, centers near the apex of Greenland; the north Pacific "low" centers on the Aleutian islands.

It is not difficult now to understand the peculiar behavior of the ice-drift of the polar seas. The Asiatic "high" with its outflowing currents pushes the ice off the Asiatic coast, while the currents inflowing toward the two "lows" impel it toward a point between the two. The Asiatic "high," however, develops more to the northeast of its center than to the northwest, and the North American area of moderately high barometer extends a tongue to the northwest between the two "lows," so that the two high areas approach each other north of the north Pacific "low" and reduce its influence upon the high latitude currents. These are therefore directed disproportionately toward the north Atlantic "low," and give to it a dominating influence. Buchan's maps of wind-directions for the winter months (when local influences are reduced to the minimum) show that the prevailing wind currents flow concentrically about the north Atlantic center from the Lena on the east to the MacKenzie on the west, a stretch of 220° longitude.

Correlation of circumpolar currents.—But in considering the circumpolar circulation as a whole, it is necessary to combine all the movements about all these centers to find the true dynamic center or the constructive pole of the winds. While such a combination cannot be accurately made from present data, it is obvious that it must place this constructive pole somewhere to the northward and westward of the north Atlantic "low" and nearer to it than to either of the other centers. The point toward which the ice-drift converges satisfies these conditions, and may be taken as nature's own practical correlation. Possibly the magnetic pole may prove to be another expression of the same correlation, made indirectly through the agency of electric and magnetic dynamics springing from atmospheric circulation.

One-sided location of "lows."—As already noted, the two areas of permanent low barometric pressure are located on the American side of the globe and have their centers, according to Hann and Buchan, less than 140° Long. ($\frac{7}{18}$ of the total 360°) apart. They are notably elongated in a general east-westerly direction, the north Atlantic area being especially extended easterly and northeasterly, and somewhat curved and reniform. If the isobaric line of 29.95 inches, which represents the average pressure for the globe, be taken as defining the low areas, their borders are only about 40° Long. apart on the American side, while they are 115° Long. apart on the Asiatic side in about the same latitude. In other words, the distance between the borders of the low areas on the American side is about one third of the distance on the Asiatic side. The distance between the borders of the "lows" is only about one half their own longitudinal diameters. The tract between the borders of the "lows" on the American side being thus relatively narrow, it might naturally be anticipated that the currents within it would be much influenced by those of the adjacent depressions, and this seems to be in a large measure realized, for the winds on the northern American plains east of the Rocky Mountains flow in the main concentric to the north Atlantic depression. On Buchan's map 52, which has a polar projection, the isobaric line of 30 inches describes nearly a circle about a point not far from the center of Greenland's ice-field. (See sketch map 2.) In a rude way the prevailing winds within this circle and for some short distance without it whirl about the Greenland center with inward tendency. The influence of the north Pacific depression does not appear to be appreciably felt east of the mountains.

Relation of moving cyclones.—It is interesting to note in this connection that many of the moving cyclones that traverse the mid-latitudes of our continent seem to take their origin in the tract between these two permanent cyclonic areas, or in the region immediately to the south of it, and that possibly they are but secondary eddies generated by the action of the great fixed ones. As before noted, the migrant eddies swing concentrically about the north Atlantic depression.

Location of present glaciation.—Coming closer home to the glacial problem, it is important to note that the two great areas of present arctic glaciation are intimately related to these two permanent cyclonic areas. The Alaskan and Greenland ice-fields not only lie within these areas of barometric depression, but are peculiarly related to them. It is, at first thought, not a little singular that, while the Alaskan ice-fields lie on the *northeast* border of the Pacific "low," the ice-fields of Greenland lie in the *northwest* quarter of the north Atlantic "low;" that is, the chief glaciations lie *between* the centers of the two permanent cyclonic areas. The apparent anomaly of maximum ice accumulation in the northwest quarter of the Greenland "low" probably finds its explanation in the following considerations:

1. The maximum precipitation (which is normally found in the southeast quarter of a "low") and the maximum ice accumulation should not theoretically be coincident; for the ice accumulation is not a true measure of the precipitation, but merely a measure of that *part* of precipitation which is frozen when it falls and survives melting and evaporation. Now in the north and west quarters a larger percentage of the precipitation is snow than in the south and east quarters, where the sum total of precipitation is greater. Moreover, the melting in the north and west quarters is obviously less than in the opposite quarters. The annual isotherms for the southeast quarter range from 35° up to 50° F., while those of the northwest quarter range from 35° down to 0° F. The ice-fields of Greenland and the lands west of it lie in the tract whose annual average is below 32° F. Iceland, whose precipitation is greater, but whose glaciation is less, lies between isothermals 35° to 40° F.

2. The configuration of the water area which wraps about Greenland gives special snow-precipitating efficiency to the winds that swing about the depression on its north side and

cross Greenland from the east and northeast. *The nature of the circulation is such that Greenland is really on the leeward side of the north Atlantic.* This is shown by the following tables of prevailing winds. The first is from the prolonged observations recorded at Godthaab and Upernivik, by Dr. Rink; the second, from those taken under the direction of General Greeley at Fort Conger in the years 1882 and 1883:

PERCENTAGES OF TIME DURING WHICH GREENLAND WINDS BLOW FROM THE DIRECTIONS NAMED

	At Upernivik Lat. 72° 47′. Long. 55° 35′				At Godthaab Lat. 64° 11′. Long. 51° 43′			
Direction	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
N.	25.5	33.9	31.9	28.8	33.1	37.4	30.3	25.5
E.	34.3	23.1	16.2	36.5	38.4	24.8	8.6	33.6
S.	15.5	20.3	28.0	18.1	16.1	21.7	32.9	22.9
W.	1.8	2.5	6.4	4.4	4.9	5.7	15.1	6.2
Calms	22.9	20.2	17.5	12.2	7.5	10.4	13.1	11.8
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

FREQUENCY AND VELOCITY OF WINDS AT FORT CONGER, LAT. 80° 44′ N., LONG. 64° 45′ W.

Direction	1881-2		1882-3	
	Times	Miles	Times	Miles
N.	393½	1522	420	2401
N. E.	761	3061	1022	4613
E.	1151½	4843	1369	4061
S. E.	678½	3605½	862	3650
S.	683½	3864½	775	4214
S. W.	678	2011	900	3059
W.	371	949	343	997
N. W.	296	731	387	1142
Calm	3408	1282	2682	50

The winds of the summer months are much influenced by local features, especially by the sea, the naked earth and the ice fields, respectively, while in the cold months a nearly uniform mantle of snow or ice covers the whole surface in common, and removes essentially all sources of variation except those of relief. Including the data of the summer months, the preponderant direction is shown by the above tables to be easterly. Omitting them, it becomes northeasterly. But in either case the dominant winds come from the north Atlantic, and justify the statement that Greenland is on the leeward side of the high north Atlantic and the adjacent part of the Arctic Ocean.

In the eastern part of the Arctic Archipelago as far south as Hudson Straits the winds are very variable, a fact quite consistent with their physiographic surroundings, and with their location well toward the interior of the north Atlantic depression.[1]

The paths of the moving cyclones.—Besides the general fact that the prevailing atmospheric currents from the Mackenzie to the Lena form a great eddy, with maximum conditions of glaciation on the north and west of its chief center near the apex of Greenland, it is to be noted that the paths of the moving "lows" are greatly influenced by the permanent depression at the center of the eddy. This is graphically shown for the north Atlantic portion of the region by Hann's map No. 36[2] herewith reproduced (sketch map 3), in which it is shown that nearly all the moving "lows" curve to the northward in courses more or less rudely spiral or concentric to the permanent "low." The larger number of paths run spirally in toward the permanent center, which suggests the conception that the great fixed cyclone is in some sense an aggregate of numerous small in-running migrant cyclones. If data were sufficient to permit the following of the complete courses of all the migrant cyclones from their origin to their extinction, a dominant system of great interest would probably be shown. As already remarked, a considerable number of these migrant cyclones originate in the American northwest.[3] These show a notable habit of sweeping southeasterly

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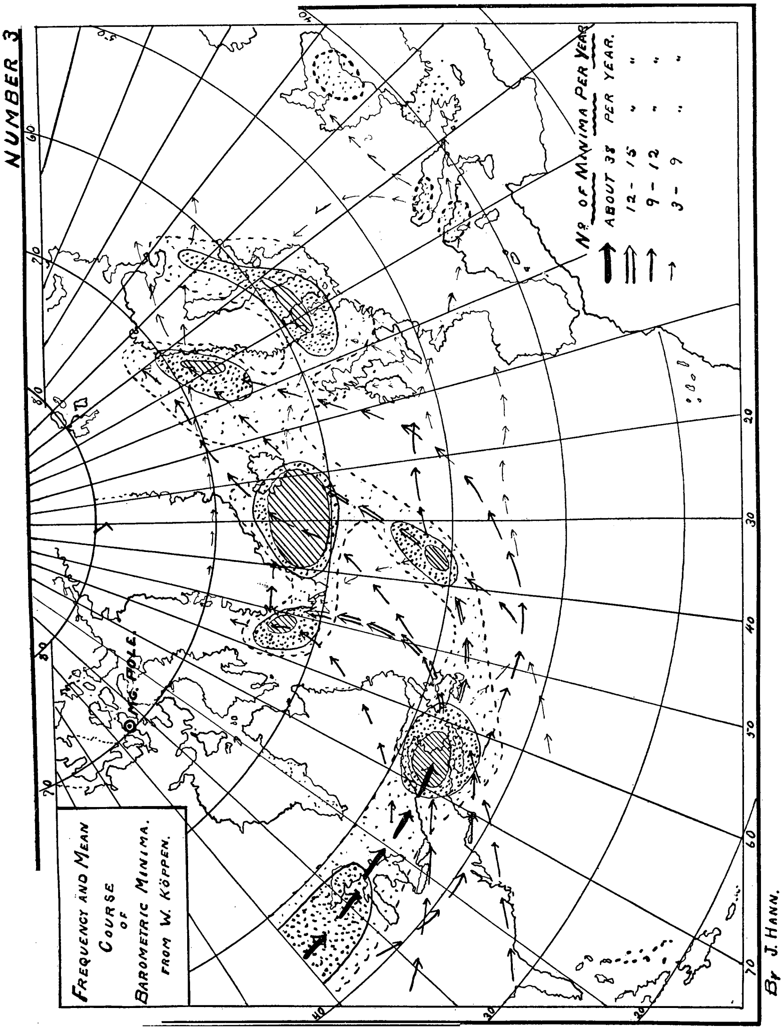
[1] I am greatly indebted to the Hon. Willis L. Moore, Chief of the United States Weather Bureau, and to Professor R. F. Stupart, of the Canadian Meteorological Service for transcripts of data relative to various high latitude stations not otherwise at my command.

[2] Berghaus' Physical Atlas.

[3] "The North American continent is the region where cyclones form in large numbers, and Europe and Asia the region where they dissipate." F. H. BIGELOW: Am. Jour. Sci., Vol. VIII, December 1, 1889, p. 443.



NUMBER 3

FREQUENCY AND MEAN COURSE OF BAROMETRIC MINIMA. FROM W. KÖPPEN.
No. OF MINIMA PER YEAR
ABOUT 38 PER YEAR.
12 - 15 " "
9 - 12 " "
3 - 9 " "
MAG. POLE
BY J. HANN.
20
30
40
50
60
70
80

into the Mississippi Valley, where they curve about and follow the courses shown on Hann's chart. These courses seem to fall into two classes, the one running spirally inward toward the center of the great fixed eddy, the other spirally outward with dispersive tendencies. A suggestion relative to the possible reason for this last feature will be given in another connection.

A more general view.—While all generalizations now entertained must be held very tentatively, because of the imperfection of present data, a general conception of the circulation of the northern part of the northern hemisphere, which will serve to bring together and give coherence and unity to the more special features which have been discussed, may be pardoned.

The whole temperate and polar region is divisible into areas of high pressure (annual average above 29.95 inches, 760 mm) in which the dominant currents are downward and outward, and areas of low pressure (annual average below 29.95 inches, 760 mm) in which the dominant currents are inward and upward. The mutual disposal of these gives a basis for a general view of the atmospheric circulation.

The high pressure loop.—In tracing the former we may start, for convenience, on the 30° latitude tract at its Atlantic node near the Azores, where it lies between 30° and 40° north latitude. Tracing it thence easterly, it inclines notably to the north, and at the meridian of 100° east, has made a northerly gain of 20° latitude. Thence onward it continues to gain in latitude, at first more rapidly and then less rapidly to about the meridian of 180°, when its course is nearly normal to the meridian, and its latitude may be roughly taken as 75°. Thence onward its course is south of east to the Mackenzie basin, and thence more southerly over the Canadian plains east of the Rocky Mountains until it again joins the high tract that normally lies near 30° latitude. It thus makes a great loop swinging around the pole, and passing near it at its climax in latitude, and enclosing the great north Atlantic eddy (see sketch map 2). The tract is accentuated by nodes of an anticyclonic nature. The chief of these is the great "high" of Asia. This protrudes to the southeast, and is constructively connected in that direction with the 30° belt, which develops a strong anticyclonic node near the California coast, beyond which it connects with the main tract which crosses the United States and the Atlantic near its normal position. Between this connection across the Pacific and the main loop before traced lies the Aleutian depression.

The high tracts of the northern hemisphere therefore form (1) a great loop embracing the great north Atlantic depression and, (2) incidentally, as it were, a minor loop embracing the north Pacific depression. The great loop is not conceived as a current, much less a whirl, but as a tract along which the upper atmosphere habitually descends with outflowing tendencies. The enclosed area of low pressure is a tract over which the lower atmosphere habitually ascends with inflowing tendencies.

Now the main loop and the main enclosed eddy lie on one side of the northern hemisphere and embrace the chief area of Pleistocene glaciation. This main loop and its enclosed eddy embrace about three fourths of the hemisphere north of 30° N. Lat. In the area left vacant, so to speak, the secondary Aleutian eddy is developed and covers the main area of the Cordilleran Pleistocene glaciation.

There can be no question that this peculiar configuration is due to physiographic influences, particularly the oblique attitude and peculiar oceanic circulation of the Atlantic, and the similar obliquity of the main body of the eastern continent. To realize the full force of this obliquity one should trace on a globe the great axis of the eastern continent from Cape Verde on the protruding portion of Africa to Cape East at the extremity of Asia, an immense spiral, and then, starting from the coast of South America near the lesser Antilles, trace the axis of the North Atlantic to the heart of the Polar sea in a similar great spiral, essentially parallel to the former. With these primary influences many secondary ones are joined, some acting concordantly to intensify the obliquity of the circulation, and others acting discordantly and tending to destroy its symmetry, and modify its configuration.

This discussion of the present circulation, too protracted for this place, yet too brief for its purpose, has seemed necessary to make clear the conception entertained respecting the agencies of localization. It has previously been urged in this paper that a reduction of the carbonic acid in the atmosphere and the consequent reduction of its heat-absorbing capacity must intensify the influence of all surface features. In the discussion of existing glaciation I have endeavored to connect the present great ice-fields genetically with the two great areas of low pressure, and to associate them with an oblique disposal of the great circulatory features. The chief centers of present glaciation lie on the borders of the American continent. The chief Pleistocene glaciations, were concentrically arranged about these centers. As has been pointed out by other students of Pleistocene glaciation, the great northeasterly ice-sheet had its western, southern and southeastern limits almost coterminous with the predominant paths of northern migrant cyclones. To complete the hypothesis of localization it is therefore only necessary to assume an intensification of the present oblique system of circulation, with a further shifting of the centers of depression in the direction of the present displacement, accompanied by a sufficient depression of temperature. And these are the effects assigned to a reduction of the atmosphere's thermal capacity due to loss of carbonic acid.

Suggestion relative to migrant cyclones.—One further feature deserves notice. If the constructive pole of the winds lies somewhere between the earth's pole and the American continent, the frictional action of the earth will affect the two sides of the eddy in opposite senses. On the western side (from the American point of view) the friction will tend to drag the bottom air toward the cyclonic center and crowd the isobars upon each other. As the lines of the wind circulation and the earth rotation cross each other obliquely, a predisposition to form gyratory or cyclonic eddies may be inferred, and this may be one of the sources of migrant cyclones which may be regarded as small eddies in the grander cyclonic movements.

On the eastern side of the pole of the winds, the earth movement tends to drag the bottom air away from the center and this is perhaps one of the reasons why the moving cyclones on that side show a tendency to dispersal, both in course and in force, as previously noted.

Possible relation to terrestrial magnetism.— It is scarcely appropriate to this paper, if it were in my power, to discuss the relations of this oblique system of atmospheric circulation to the oblique system of terrestrial magnetism. Crudely stated, the notion entertained is that an atmosphere charged with electricity, circulating obliquely about a rotating earth which is inset with magnetic and magnetizable matter, might give rise to a magnetic system which should express the dynamic resultant of the atmospheric circulation. A comparison of the magnetic and atmospheric charts shows so many points of resemblance, some of which are striking *peculiarities*, as perhaps to justify this tentative notion until the mystery of the earth's magnetism be solved. Connected with terrestrial magnetism are auroral manifestations whose distribution is notably similar to that of the chief Pleistocene glaciation, as was remarked many years ago when first the progress of exploration outlined the extent of the glacial deposits. It can hardly be presumed that either terrestrial magnetism or auroral displays have in themselves any causal connection with glaciation, but if they are dependencies of atmospheric circulation they become eminently serviceable to glacial students by affording a tangible concrete expression of the dynamic correlation of the atmospheric circulation, free from the intricate complexities of the latter; in short, a natural resultant at easy command. The verity of the notion must, of course, depend wholly on the outcome of magnetic investigations on their own lines, which happily are now being vigorously prosecuted.

SUGGESTIONS RELATIVE TO MINOR GLACIAL OSCILLATIONS

It has already been noted that besides the oscillations of epochal order there were subsidiary ones which left their record in a series of concentric moraines which corrugate the individual sheets of glacial débris. The latest drift sheets show this best. That designated Wisconsin is accentuated by nearly a score of peripheral ridges. In a recent admirable paper by Keilhack[1] it is shown that similar lines of halt, and perhaps of minor advance, mark the corresponding European glacial sheet as deployed on the plains of north Germany; indeed, even in some of the greater details, a striking correspondence is traceable between the two series, whose general identity in age and kind were long since noted by Salisbury.[2] These minor oscillatory phenomena seem, therefore, sufficiently general and sufficiently important to require an explanation, and this explanation is not necessarily connected with the fundamental cause of glaciation. The preceding discussion carries in itself a suggestion which is worthy of note in passing. If the localization of the great ice-sheets was dependent on the general circulation of the atmosphere, any periodic shifting of the circulation of moderate magnitude might be competent to cause a shifting of the ice-sheets of corresponding nature. There are historical facts that give some color to the notion that such shiftings have taken place within the period of human records. The oscillations of existing glaciers point in a similar direction. There is clearly a secular shifting of terrestrial magnetism, but the nature of its cycle is yet undetermined. Current opinion gives it a periodicity which would quite well satisfy the demands of the concentric moraines.

GLACIATION NEAR THE CLOSE OF THE PALEOZOIC ERA

While the occurrence of extensive glaciation in India, Australia and South Africa near the close of the Paleozoic era may be regarded as fully established, a specific discussion of its origin along the lines of an atmospheric hypothesis presents formidable difficulties, because the exact date of the glaciation, its immediate antecedents and the nature of contemporaneous conditions in other parts of the world are not yet satisfactorily determined. No embarrassment attends a merely general application of the atmospheric hypothesis set forth in this paper, and perhaps it would be wise in the present state of knowledge to be content with such general application. But the main purpose of the paper — to develop a *working* hypothesis, helpful in the promotion of investigation — would be measurably defeated thereby, for a general theory merely supposed to be applicable in some indefinite way, not even specifically thought out, much less shaped to promote definite inquiry, falls short of working qualities. Were the Paleozoic glaciation a high-latitude phenomenon which could be referred to the same category as the Pleistocene glaciation, we might well leave specific discussion until further data were afforded, for few additional doubts as to the verity of the hypothesis and probably few new lines of inquiry would be raised. But the Paleozoic glaciation presents characters so extraordinary as to render it the supreme problem of glaciation. In it every hypothesis finds its severest test. No hypothesis that does not, in some remote way at least, approach an elucidation of this supreme case can have serious claims to acceptance as a working theory. It is, therefore, imperative to frankly and fully recognize this crucial problem and deal with its difficulties as well as existing data permit. A really satisfactory discussion is quite impossible in the present nature of the case. The attendant atmospheric and geographic conditions must be postulated, consciously or unconsciously, but the data for such postulates are imperfect and their interpretation is at best not more than probable. It is hoped, however, that fairly good reasons can be assigned for everything assumed in this paper.

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[1] Die Stillstandslagen des letzten Inlandeises und die hydrographische Entwickelung des pommerschen Küstengebietes. Separatabdruck aus dem Jahrbuch der königl. preuss. geologischen Landesanstalt für 1898. Berlin.

[2] Terminal Moraines in North Germany. Am. Jour. Sci., Vol. XXXV, p. 401. Series 3.

The essential facts that make the Paleozoic glaciation a peculiarly strenuous problem are these:

1. It occurred in an early stage of the earth's history. No appeal can, therefore, be made to an advanced state of secular cooling leading on the "final winter" nor to any senile condition

inherent in an aged earth. If the traditional view that the primitive atmosphere constituted a vast store that has been gradually drawn upon throughout the ages in the formation of the coals and carbonates, and was their chief source, the atmosphere at the close of the Paleozoic era must still have been rich, deep and dense to a degree far surpassing the present atmospheric state, for vast deposits of coal and carbonates have since been made through its agency. One of the most conservative as well as most competent estimates of the consumption of carbonic acid since the Paleozoic era places it at 5000 times the present content. To be conservative, let this be halved and halved again, and still the content of carbonic acid is 1250 times that of the present. This atmosphere was so different from that of the Pleistocene and present period as to render uncertain, if not inapplicable, all arguments founded upon the phenomena of the latter. The question of the constitution of the Paleozoic atmosphere is, therefore, fundamental, because it affects the substratum of all arguments based on present or recent experience. Even with the above excessively reduced estimate, do we reach an atmospheric environment in which any known agency applicable to the case can be reasonably postulated as competent to cause general glaciation ? In such an atmosphere, or in any atmosphere greatly richer than the present in heat-absorbing and heat-retaining qualities, are there any sufficient grounds for seriously supposing that any of the putative causes of Pleistocene glaciation, whether topographic, geographic, latitudinal or astronomical, could produce such a glaciation as is recorded under the tropics of the far Orient. It is not a part of the purpose or the method of this paper to antagonize other hypotheses, but rather to invite their development into working coöperation and competition with that herewith advanced ; but a wholesome interaction of hypotheses will be best attained by eliminating wholly untenable grounds and by bringing all hypotheses within the limital conditions of competency. It is, therefore, no transgression of my purpose to urge the question whether all hypotheses are not required, for their own conservation, to accept so much of the fundamental postulates of the atmospheric hypothesis as are needful to give an atmosphere compatible with glaciation under such other conditions as prevailed in India, Australia and South Africa in the later Paleozoic.

2. The localization was most extraordinary. The chief areas lay under the tropics — the Indian, under the Tropic of Cancer and the Australian and South African, under the Tropic of Capricorn. The Indian area stretched southward to 17° 20′ N. Lat. and northward to the vicinity of 35°. The Australian area stretched north to 20° 30′ S. Lat. and southward (in Tasmania) to 42°. The extent of the South African area is less well known, but centers about 30° S. Lat. It appears then that on both sides of the equator glaciation reached two or three degrees within the tropics, while in the opposite direction general glaciation has not been traced beyond 42° To the south this signifies little because of the prevalence of the sea. To the north the apparent limitation is very singular and doubtless very significant. It cannot, however, be positively asserted that glaciation did not prevail in the higher latitudes, but no decisive evidence of it has yet been discovered. At the same time it must be recognized that many evidences of remarkable transportation and of unusual bowlder accumulation, and indeed of occasional striation have been reported, and that these have been attributed to glacial agencies by geologists of high standing. It cannot be affirmed at present that these phenomena were precisely contemporaneous with the glacial deposits of the oriental tropics, but they were nearly so.

In the southern portion of Brazil there are deposits strikingly similar to the glacial beds of Africa and Australia, but no striation or distinctive marks of glaciation have yet been authoritatively reported.

The southernmost extent of the lowland Pleistocene glaciation was about 37° N. Lat. The Paleozoic glaciation, therefore, reached 20° farther.

The altitude of the glaciation.—Respecting the altitude at which the Paleozoic glaciation took place, it is to be remarked that in some cases there is so intimate an association with marine deposits as to indicate that the ice reached the sea level and discharged icebergs. The associated marine fossils do not seem susceptible of explanation by mechanical admixture through the action of the ice, because of their condition and their position in the embracing sediments. Oldham[1] reports that certain bowlder-bearing mudstones "contain delicate Fenestellæ and bivalve shells, with the valves still united, showing that they had lived, died, and been tranquilly preserved where they are now found, and proving, as conclusively as the matrix in which they are preserved, that they could never have been exposed to any currents of sufficient force and rapidity to transport the blocks now found lying side by side with them. These included fragments of rock are of all sizes from a few inches to several feet in diameter."

These and other evidences leave little room to doubt that a part of the glaciation at least affected low horizons. On the other hand, most of the glacial beds are so related to their own glaciated floor as to show that they were formed by land ice. This is confirmed by the nature of the striæ, the relations of the transported blocks to their source, and the association of the glacial beds with fresh-water deposits. At present some of the glacial beds are 3000 to 3500 feet above sea level (Tasmania), but in general they are much lower. How much of this altitude is due to subsequent changes I do not know. There is, however, much evidence that the glaciation was not of the alpine type, or at least not simply of the alpine type. It spread over broad areas of moderate slope.

In kind of glaciation and in topographic relations the Paleozoic phenomena seem to have been of the same class as the Pleistocene.

Approximate age.—Professor David and other cautious writers of recent date do not attempt to locate the horizon of this glaciation nearer than Permo-Carboniferous. It is certain that in the Salt Range in northwestern India a Productus fauna overlies the bowlder beds. From this and other paleontological evidence it would seem that the lowest of the glacial deposits at least antedated the disappearance of the Permian faunas from the seas.[1] It is unfortunate that the peculiar nature of the formation, and the not less peculiar nature of the associated flora, make it impossible at present to fix its exact horizon in terms of the European and American standards, so that the contemporaneous conditions in these regions could be determined. However, for the application of the atmospheric hypothesis the foremost question is the relationship of glaciation to the great agencies that affected the constitution of the atmosphere. These agencies were (1) the formation of coal, and (2) chemical reaction between the air and the earth's surface.

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[1] R. D. OLDHAM: Rec. Geol. Surv. India, XIX, 1886.

1. Relative to the first, it is certain that the glaciation closely followed the great coal-depositing period, and indeed fell in with the latest stages. In Australia there are considerable deposits of coal (the Gretna Coal Measures, embracing twenty to forty feet of coal) deposited "between the erratic-bearing horizon of the lower marine series and the similar horizon of the upper marine series" (David).[2] If, therefore, we look to the deposition of coal as the agency of atmospheric exhaustion, the relationship is nearly ideal.

2. If we look to elevation, and consequent large earth-contact, the relationship does not appear to be what theory would demand. It can scarcely be questioned that at the close of the Paleozoic period there was a very unusual surface movement, affecting great areas of the earth's surface and increasing largely the exposure of the land. The period appears to have been altogether comparable to that at the close of the Tertiary period. If we were seeking the cause of the glaciation assigned to the Triassic, or the occasion of the salt and gypsum deposits

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[1] There is some evidence of another glacial horizon at or about the base of the Triassic (well indicated in White's excellent synopsis, Am. Geol., May 1889, table, p. 315). The present discussion will, however, be confined to the lower horizon, that of the Talchirs and their equivalents.

[2] Quarterly Jour. Geol. Soc., Vol. LII, May 1896, p. 300.

so widely prevalent in the Permian and Triassic formations, this elevatory movement would stand in the proper relations. But, if present evidence is to be trusted, it does not stand in the proper antecedent relations to the Permo-Carboniferous glaciation, at least not as the primary agency. Still, though there is an absence of evidence of large exposure of the land surface to atmospheric degradation for a notable period preceding the Permo-Carboniferous glaciation, there are good grounds for believing that the great era-closing movement of the Paleozoic had made notable advance even at this time.

The Gondwána elevation.—The glacial beds under consideration form the basal members of the remarkable Gondwána series, the chief members of which are land and fresh-water deposits. These in themselves imply a recently rejuvenated topography, for an ancient topography has a perfected drainage system and adjusted gradients. It is the dominant belief of those who have most studied the region circumjacent to the Indian Ocean, that the formation of the Gondwána series and the development and distribution of the remarkable Glossopteris flora, imply extensions and connections of land of a somewhat unusual kind. If this belief were accepted to the full extent urged by its strongest advocates, it would in itself involve a very large exposure. I am not disposed, however, to force the doctrine of a Gondwána continent beyond the most modest limits, however much it might contribute to a favorable reception of the hypothesis under discussion. It appears to me that the distribution of the Glossopteris flora may be in some notable part a climatic rather than a topographic effect; that is to say, the peculiar atmospheric conditions, of which glaciation was the supreme expression, distinguished that quarter of the globe from the rest, and may in themselves have controlled the distribution of the peculiar flora in question. It may therefore only be necessary to postulate such an extension of the land as was required to permit the migration of the flora and its companion fauna.

However this may be, it is very generally agreed that some notable land extension prevailed as early as the origination and distribution of the Glossopteris flora. It will be quite conservative to assume that this involved a land connection between India and Australia, and probably New Zealand, the connection presumably lying along the submerged platform which even to this day stretches southeasterly from Asia to the islands in question with slight interruptions. It is not improbable that between India and South Africa at least a partial bridge was formed by the elevation of the submerged plateau on which Madagascar and the Seychelles rest, together with the tract now accentuated by the Maldive islands.

A connection with South America (where the Glossopteris flora also appeared — southern Brazil and Argentina) involving the least radical departure from modern configuration, may have been made via New Zealand and the Antarctic continent. This, I believe, also best satisfies the general tenor of paleontological evidence.

If the geographic changes were confined to such connections and extensions of land as these, and to such moderate elevations as the nature of the glacial beds and the associated deposits seem to imply, and to such changes in the northern hemisphere as can fairly be assigned to the Permo-Carboniferous period, there does not seem to be adequate ground for attributing a very exceptional depletion of the atmosphere to land-contact alone, or chiefly, though it may have made some notable contribution in that direction.

Effects of atmospheric depletion by coal deposition.—We therefore turn to coal-formation as the effective alternative. There are no reliable estimates of the total carbon in the coal and carbonaceous deposits of the Carboniferous period, but such approximations as have been made seem to show that it equals several times the present atmospheric content, and that its extraction superadded to the increasing formation of carbonates resulting from the rising land would have been competent to reduce to the point of glaciation an atmosphere three or four times as rich in carbon dioxide as the present; in other words, such an atmosphere as the sub-Carboniferous climate seems to imply.

A question of no small interest is the special kind of effect which an atmosphere reduced by coal formation would induce as distinguished from that induced by depletion through earth-contact. In the latter, as already set forth, bicarbonates were the chief product, and carbon dioxide, temporarily locked up, played a very important part. Through the peculiar agency of the ocean this "loose" carbon dioxide hastened the development of glaciation, prepared the conditions for strong reaction and accelerated the reaction when inaugurated. In the formation of coal and like products no such effective temporary factor is produced. The carbon is, to be sure, temporarily held in the vegetation, but so much as decays goes directly back into the atmosphere, in the main, and the rest becomes permanently fixed. Neither part goes into an intermediate state of reserve, subject to being called forth by change of conditions as in the case of the second equivalent of the bicarbonates of the ocean. The action is somewhat analagous to the original carbonation of the silicates of the crystalline rocks in which the first equivalent of carbon dioxide when once united remains fixed (barring accidents to which coal is also liable), but in this case there is also a second equivalent of carbon dioxide temporarily locked up so long as a state of solution is maintained. Succinctly stated, without the unessential qualifications: (1) Depletion by coal formation is accompanied by no intensifying and reactive factor; (2) Depletion by conversion of silicates into carbonates is accompanied by an intensifying and reactive factor; (3) Depletion by the solution of limestone is wholly temporary in nature and specially capable of promoting intensification and reaction.

If, therefore, the impoverishment of the atmosphere as the prerequisite of glaciation in Permo-Carboniferous times was due, in the main, to the extraction of carbon in the form of coal and like deposits, there was absent, to that extent, the factor to which the hastening of glaciation and of reaction is assigned. Before glaciation could be affected in the measurable absence of this accelerating agent, it was necessary for the permanent depletion to go to greater lengths. Moreover the depletion when once affected was essentially a non-reactive one. Of course the reactive factor was never really absent, for the formation and solution of carbonates was always in progress. In this case it is merely supposed to be the minor rather than the major factor. It is inferred, therefore, that a higher stage of permanent depletion of the atmosphere was reached before glaciation ensued through coal formation than would have been the case had the glaciation been produced by the formation of carbonates. To this, in a measure at least, is attributed the conditions which made it possible for the glaciation to affect lower latitudes in Permo-Carboniferous times than they did in Pleistocene times. As before noted, the Permo-Carboniferous glaciation extended 20° nearer to the equator than the Pleistocene.

The localization of the Permo-Carboniferous glaciation.— It remains to consider the remarkable localization of this ancient glaciation. The general principles involved are assumed to have been the same as those already applied to the Pleistocene problem, but the geographic factors were quite different, and it is here that the lack of complete data is most keenly felt. In Pleistocene times, as also at present, certain great geographical features are thought to have given a pronouncedly oblique circulation to the air currents of the northern hemisphere. In the southern hemisphere at present a much greater approach to symmetrical circulation prevails because great oblique features are absent. It is postulated that the configuration of Permo-Carboniferous lands and oceans was such as to seriously disturb the symmetry of the atmospheric and oceanic circulation of that hemisphere, and to give it peculiar form and special intensity.

The geographic features of the Permo-Carboniferous period.—The assigned changes introduced by the development of Gondwána land have been mentioned. These are thought to have prolonged the Asiatic continent southeasterly to Australia, and probably to New Zealand, and perhaps to the Antarctic land. This prolongation, taken with its backward projection across Asia and Europe, constituted an oblique feature of great extension. It also interposed a barrier which very notably modified the water connections of the Pacific and Indian oceans. The warm equatorial currents which now flow through the numerous straits of the East Indies and add warmth to the Indian Ocean were turned back, and their heat retained in the Pacific. At the same time the cold currents of the southern Indian and the adjacent Antarctic oceans were shut out measurably or wholly from the Pacific, and turned northward into the equatorial portion of the Indian Ocean. There was thus a concentration of heat in the one and of cold in the other. If the suggested connection of New Zealand with the Antarctic continent was made, these cold southern waters would have been effectively shut out from the Pacific and forced to circulate through the Indian Ocean. If the other conservative changes suggested to meet the demands of the Gondwána phenomena were realities, the Indian Ocean took the form of a great triangle with a very broad base in the antarctic regions, and a narrowed apex reaching across the equator to the vicinity of the Indian glaciation.

In the north Atlantic region there is evidence that the great readjustment which closed the Paleozoic era had made notable advances at the probable time of the Oriental glaciation The New Red Sandstone of western Europe is not unlike the Gondwána series in general characters, and indicates a like rejuvenated land. Within it also are found arkose, conglomerates and breccias, often formed of large, far-transported blocks. "Some of these blocks are three feet in diameter, and show distinct striation. These Permian drift beds, according to Ramsay, cannot be distinguished by any essential character from modern glacial drifts, and he has no doubt that they were ice-borne, and, consequently, that there was a glacial period during the accumulation of the Lower Permian deposits of the center of England."[1] There is good ground to believe that previous to the formation of these deposits the land on the European border of the Atlantic had risen relatively. There are similar evidences on the American side. The close relations between the land faunas and floras on the two continents strongly imply a free land connection. This is most pointedly indicated by the distribution of the amphibians of the Carboniferous and Permian periods. The Branchiosauria, Aistopoda, Microsauria, and Labyrinthodontia vera were all represented on both continents, and unless the doctrine of parallel evolution be pushed to a seeming extreme, the only satisfactory explanation is an ample land connection. The amphibians of today are fatally affected by salt water, and even their eggs lose their vitality after a short submergence in it. It cannot be positively affirmed that this was true of the Carboniferous amphibians, but the presumptions appear to lie in that line. At any rate the occurrence of all the leading branches on both continents renders it quite improbable that a broad ocean intervened. It is therefore assumed that the Atlantic Ocean was restricted at the north by such connection. To be definite, it is assumed that it essentially terminated south of the Greenland-Iceland-Faroe platform, or possibly south of the Telegraphic plateau.

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[1] SIR ARCHIBALD GEIKIE: Text-Book of Geology, p. 753.

There are few data that give specific indications as to the configuration of the north border of the Pacific at this time, but the considerations that have just been urged with reference to the distribution of the fauna and flora are apparently best satisfied by supposing an emergence of the very slightly submerged continental platform of the arctic region generally. This is in harmony with the history of the preceding Paleozoic periods during which the Eurasian and North American continents were essentially a unit and free migration from one to the other was an oft-repeated, if not predominant, phenomenon. If this be the true inference the Pacific Ocean was limited at the north to about 60° Lat.

In equatorial latitudes it is not improbable that the Atlantic and Pacific oceans were united between the main bodies of the North American and South American continents, so that a commingling of waters took place here not unlike that which now obtains between the Pacific and Indian oceans.

It is not improbable also, judging from the distribution of Permian marine beds, that inland seas extended along the

Mediterranean tract into eastern Europe and perhaps to the Caspian-Ural region of Asia; indeed, it is not altogether improbable that straits or narrow seas may have connected with the apex of the Indian ocean. At least in the later Permian times the marine faunas of India and of Europe were notably similar, and in the early Mesozoic they became so nearly identical as to make a connection along this line extremely probable.

Effect of the supposed geographic changes on atmospheric circulation.—While none of these postulated changes involve great terrestrial movements, or depart widely from the rather definite indications of the phenomena concerned, it will be seen upon a study of the resulting distribution of land and water that they probably profoundly affected the circulation of the atmosphere. The limitation of the Atlantic at the north by the European-American connection rendered it essentially an equatorial and warm temperate ocean. Its present high-latitude connection, involving the transportation of vast quantities of ice and cold water into it from polar regions and the reciprocal loss of heat borne into the high latitudes by the Gulf Stream, was eliminated. The atmospheric function of the Atlantic was, therefore, radically changed. That great oblique factor to which was assigned so large a function in the localization of Pleistocene glaciation, was largely absent from the Permo-Carboniferous circulation. To the similar restriction attributed to the north Pacific a minor limitation of a like kind may be assigned. Instead, therefore, of a polar sea exchanging its thermal properties with an equatorial sea, as at present, there would be substituted a prevailing polar land, relieved probably only by the deep basin of the Arctic sea, whose limited extent and land-locked situation would render it little more significant in general climatology than the present Mediterranean.

On the other hand, very notable oblique features appear in the equatorial and southern regions. The postulated changes of the Pacific Ocean, by shutting off its connections with the Indian Ocean, probably brought into effective influence its long northwesterly and southeasterly trend, now neutralized by its westward connections. In other words, the somewhat balanced distribution of the present Pacific was replaced by an effective obliquity which could scarcely have failed to powerfully influence the general circulation of the Paleozoic atmosphere. The northwest-southeasterly extension of the great Eurasian-Australian land paralleled this and intensified its effects. In other words, the Pacific Ocean and the parallel Eurasian-Australian continent constituted, in Paleozoic times, a couplet of oblique features that were chiefly effective in the equatorial zone and the southern hemisphere. They replaced the similar pair now formed by the north Atlantic and the eastern continent. It is inferred, therefore, that an obliquity of circulation of a pronounced order prevailed in Permo-Carboniferous times, by virtue of which the southern hemisphere was brought under the influence of meteorological agencies analogous to those that in Pleistocene times affected the northern hemisphere.

Some differences, however, are to be noted. The equatorial zone was then profoundly affected by the oblique features which lay directly athwart it. In addition to this there was the peculiar configuration of the Indian Ocean already set forth, namely, a broad, open mouth extended to the Antarctic polar regions, with a convergence to a narrow equatorial apex 20° or more north of the equator. The general course of the circulation in this may be assumed to have been much as it is today; that is, a movement in the polar latitudes, at first northerly and easterly, then curving about to the northward and northwestward as it approached the equatorial zone, and at length returning to the southwest along the African coast, thus forming a free circulation between the high latitudes and the low latitudes, with high latitude influences greatly preponderant. This circulation in Paleozoic times may be reasonably assumed to have been much more intense than at the present time, first, because there were then, by hypothesis, greater intensities of temperature, and second, because a larger percentage of the Antarctic waters were forced to flow into the apex of the Indian Ocean by the configuration of the land. This last statement would hold true even if New Zealand were not connected with the Antarctic continent and South America, for the avenue of escape toward the Pacific would be circumscribed by the minimum elevations which the Gondwána phenomena seem to require. If the Antarctic-South-American connection were made, it would form a barrier to circumpolar circulation, and all the polar ice-drift from South America to New Zealand would doubtless be forced northeasterly into the Indian Ocean. This would certainly lend great intensity to the circulation of the polar currents through the Indian Ocean. The temperature of the latter would therefore be radically affected by the immense quantities of ice and cold water carried through it by this intensified circulation under the atmospheric conditions postulated. A like profound influence upon the overlying atmosphere must necessarily have followed. The narrow apex of the ocean under the tropics would probably have afforded little relief from the dominance of these currents.

If this cold area be contrasted with the heated state which should naturally prevail in the Pacific Ocean, because of its vast breadth under the equator, its limitations at the north and its somewhat narrow communication at the south (particularly if it be shut off from the Antarctic flow past New Zealand) should give rise to antithetical conditions of temperature and pressure sufficient to radically influence the general circulation of the southern hemisphere. It is conceived that this extraordinary couplet might even introduce a systematic exchange of atmospheres between the northern and the southern hemispheres, consisting essentially of a cold north-seeking current flowing across the Indian Ocean into the northern hemisphere, correlated with a warm return current flowing from the northern to the southern hemisphere across the tropical regions of the Pacific, but this conception is not regarded as a vital part of the hypothesis.

The configuration of the Atlantic is supposed to have caused it to play a subordinate part, the northern portion becoming an auxiliary of the Pacific and the southern portion more or less largely an auxiliary of the Indian Ocean. If we assume that the Gondwána extension connected New Zealand with the Antarctic lands and South America, the ocean currents may be pictured as sweeping eastward from South America along the icy borders of the Antarctic continent into the great bay south of Australia, out of which they recurved and flowed northward across the equator to the Indian peninsula, which they freely bathed, and, returning along the supposed Gondwána connection, wrapped about South Africa and then flowed northward toward the equatorial regions, a portion then curving backwards and descending the coast of South America to complete the circuit. Such a circulation would throw perhaps two thirds of the antarctic influence into the Indian Ocean. On the other hand, seven eighths or more of the equatorial influence would probably be brought to bear upon the Atlantic and Pacific oceans. As a result these oceans, notwithstanding the impoverished condition of the atmosphere, received and retained a large percentage of the sun's heat.

Referring to the principles stated earlier in this discussion, it may be remembered that it was noted that a diathermous atmosphere permits a larger part of the sun's heat to reach the surface of the earth than a thermally opaque atmosphere, and that the portion which falls upon the ocean for the most part penetrates it until it is absorbed. A certain part, to be sure, is reflected, but in the zone of nearly vertical rays this is reduced to the minimum. As the result of the ocean's ability to absorb and retain heat, the diathermacy of the atmosphere is of less consequence in equatorial oceanic regions than in land tracts and hence the great equatorial oceans may have remained measurably warm throughout the glacial period.

It is conceived, therefore, that under these conditions, glaciation may have been produced in exceptionally low latitudes, and that its distribution was closely associated with the Indian Ocean. At the same time it is conceived that the lands immediately adjacent to the Atlantic and Pacific oceans, especially in low latitudes, were so far affected by the favorable thermal condition of those great bodies as to enjoy relatively mild temperatures, at least temperatures sufficiently genial to save them and the adjacent lands from the exterminating effects that might naturally be associated with a glaciation in the tropics.

Relative to the more specific location of the Permo-Carboniferous glaciation, it may be noted that a tendency to form "lows" in India, Australia, and South Africa, not far from the ancient glaciated areas, is observable even under the present conditions. It is presumed that much more pronounced eddies were, in Permo-Carboniferous times, located on the borders of the cold belt formed by the intensified antarctic circulation and that these determined the areas of specific glaciation.

Conditions in the northern hemisphere.—In the arctic regions, a very low temperature may be confidently postulated under the supposed conditions, because of the extent of the land and the absence of oceanic circulation between the high north and the equatorial regions. A Siberian climate of an intensified order is therefore assumed to have prevailed over the high latitudes of the northern hemisphere. This may doubtless have given rise to limited accumulations of snow in favored localities, developing into glaciers, but on account of the general low precipitation and the dryness of the atmosphere, giving rise to large evaporation, this may not have become a pronounced fact. In so far as glacial deposits originated in the interior of the land they would be liable to destruction by surface denudation before submergence. The Permo-Triassic land period was long. Here and there, as already noted, there are phenomena which find their easiest explanation in glaciation and ice transportation. It is to be anticipated that, if this view be correct, further indications of severe temperature in northern latitudes will be developed in the course of future studies. It may be remarked that there is now nearly as much evidence of Permian glaciation in the northern hemisphere in regions away from mountains as there is of Pleistocene glaciation in the southern hemisphere in like situations.

As remarked at the outset of this part of the paper, a really satisfactory discussion of the Permo-Carboniferous glaciation.is impossible in the present state of knowledge. I am by no means blind to the uncertain factors that inhere, at once, in the time relations, in the geographic features, and in the meteorological inferences drawn from them. The most that could be hoped from an attempt to explain so extraordinary phenomena in so imperfect a condition of the data is to suggest the general direction in which, perchance, the truth may ultimately be found to lie.

T. C. CHAMBERLIN.